

# Safe and Sustainable Energy with LIFE

*A laser-based fusion system could supply a considerable fraction of the nation's—and the world's—carbon-free electricity needs.*

**T**HE planet faces a tremendous challenge this century to close the gap between projected energy demand and the supply of sustainable, carbon-free, affordable energy. Today, 80 percent of the world's total primary energy demand is met with fossil fuels, which emit significant quantities of carbon dioxide (CO<sub>2</sub>), a greenhouse gas, into the atmosphere. This situation has implications both for our geopolitical energy security as well as for the global climate and ecosystem.

Energy experts say the global energy system cannot be “de-carbonized” and the climate cannot be stabilized without an energy technology revolution and breakthrough concepts. For their part, Livermore researchers are exploring the idea of a fusion-based system known as Laser Inertial Fusion Energy, or LIFE.

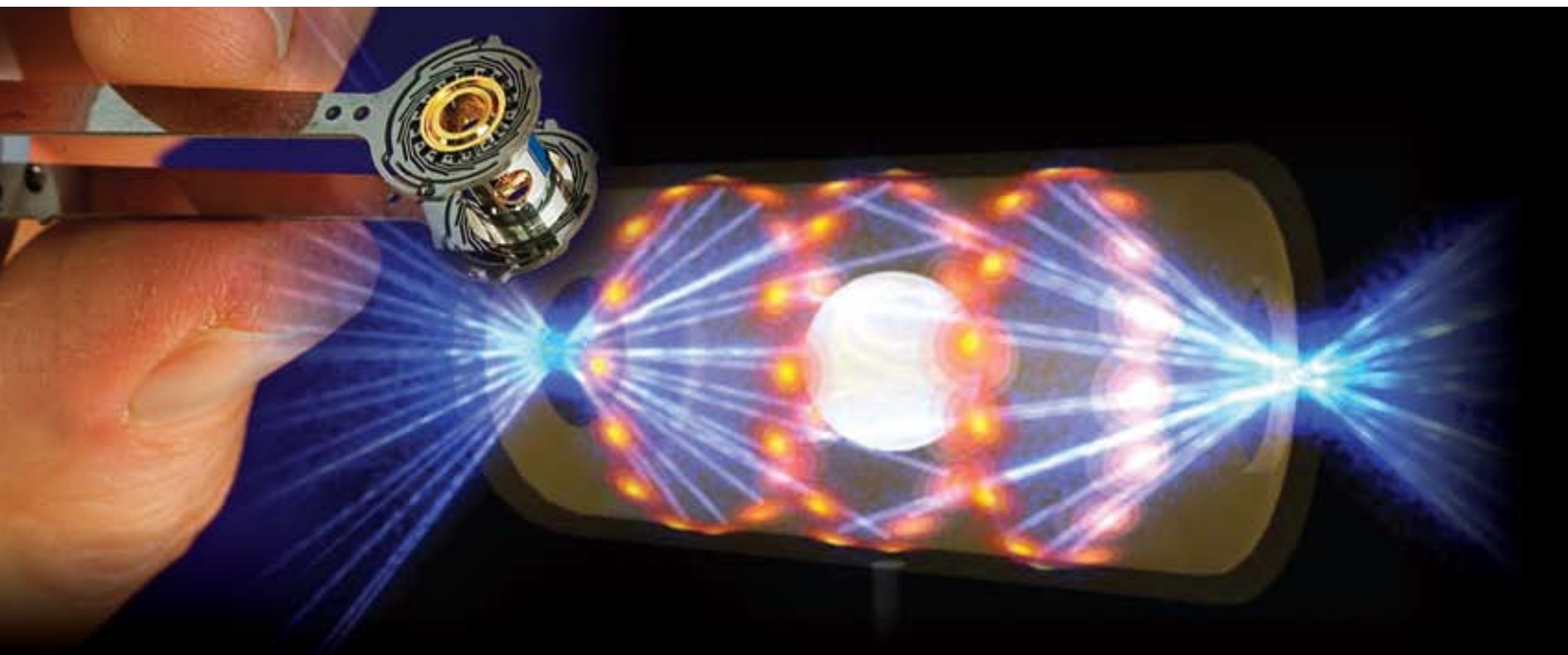
LIFE builds on technology developed for the National Ignition Facility (NIF) and promises safe, carbon-free, and sustainable energy. LIFE offers many compelling advantages, either as a pure fusion energy source or as one that combines the best aspects of fusion and fission energy systems.

According to Ed Moses, principal associate director of NIF and Photon Science, a LIFE power plant is a logical evolution of NIF, which is now operational, and will be dedicated on May 29, 2009. It is the world's largest and highest energy laser



Ignition experiments with the National Ignition Facility (NIF) will culminate decades of inertial confinement fusion research and development, opening the door to previously inaccessible physical regimes and making possible a fusion-based power plant called LIFE (Laser Inertial Fusion Energy).





Above left, a fully assembled ignition target incorporates a capsule assembly, hohlraum, and a surrounding thermal-mechanical package with silicon cooling arms. An artist's rendering shows a 9-millimeter-long hohlraum with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur. NIF's computer control system (below) precisely synchronizes thousands of components. On the next page is the main NIF facility.



and the cornerstone experimental facility for stockpile stewardship, the National Nuclear Security Administration's program to assure the safety and reliability of the U.S. nuclear weapons stockpile. The largest single scientific project ever successfully completed by the Department of Energy (DOE), NIF culminates nearly 50 years of research in inertial confinement fusion and high-energy-density science.

In the next few years, experiments on NIF are expected to demonstrate, for the first time, inertial confinement fusion and energy gain, in which more energy is released from a 2-millimeter-diameter target filled with deuterium-tritium fuel than is deposited by NIF's 192 laser beams. With preparations for the first laser fusion experiments well under way, Livermore researchers have been exploring the revolutionary concept of an electrical power plant that is a logical extension of NIF and the knowledge it will generate from planned ignition experiments.

The LIFE design starts with a 10- to 20-megawatt (MW) high-average-power laser system that produces fusion reactions at 10 to 15 times per second. As in NIF, multiple LIFE laser beams will precisely converge on deuterium-tritium fusion targets, producing 350 to 500 MW of fusion energy. The pulsed fusion reactions will produce high-energy neutrons, which then bombard a spherical blanket

containing a high-heat-capacity lithium-based molten salt that can convert the energy of the neutrons into heat to produce either steam or another hot gas that will be used to generate electricity.

In addition, the LIFE engine design can be "charged" with fission fuel. The resulting fission reactions will produce additional energy that can be harvested for electricity production. Moreover, by using depleted uranium or spent nuclear fuel from existing nuclear power plants in the blanket, a LIFE engine will be capable of burning the by-products of the current nuclear fuel cycle. Because the fusion neutrons are produced independently of the fission process, the fission fuel could be used without reprocessing. In this way, LIFE may be able to consume nuclear waste as fuel, mitigate against further nuclear proliferation, and provide long-term sustainability of carbon-free energy. A LIFE engine, via pure fusion or through the combination of fusion and fission, will generate the steady heat required to drive turbines for generating from 1,000 to 2,500 MW of safe, environmentally attractive electric power 24 hours a day for decades. (See the box on p. 11.)

### On the Path to Pure Fusion Energy

Livermore expects to achieve scientific demonstration of fusion ignition and energy gain (output fusion energy/input

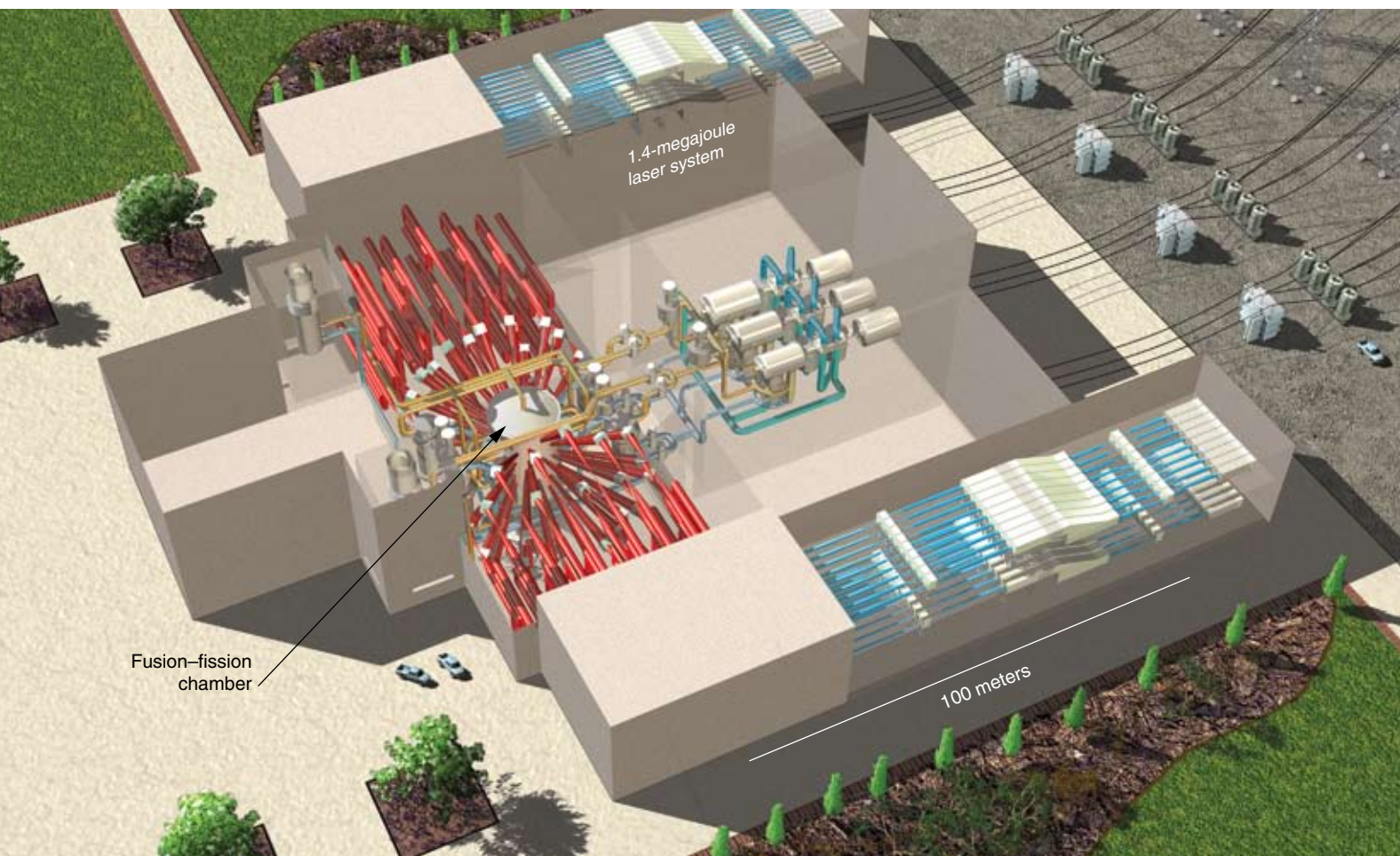
laser energy) in the laboratory in the next few years. Moses says that successful demonstration of ignition and net energy gain will be a "transforming event" and is certain to focus attention on fusion as a significant energy option. The fusion yields needed for commercial fusion energy (approximately 200 megajoules at 10 hertz) will require continuing research and development that will be pursued at NIF and with the Laboratory's scientific and industrial partners around the world.

In addition, Livermore scientists believe that by combining the best aspects of fusion and fission, a LIFE-based fusion-fission solution could provide safe, carbon-free sustainable power while minimizing concerns and drawbacks associated with the current nuclear energy fuel cycle.

LIFE chief engineer, Jeff Latkowski, points out that current nuclear power plants supply about 16 percent of the world's electricity needs. However, questions remain regarding the potential diversion of nuclear technologies and materials for weapons applications and the long-term sustainability of the uranium fuel supply. Furthermore, today's nuclear power plants generate large volumes of long-lived nuclear waste that must be either reprocessed or stored in repositories designed to remain intact for many thousands of years. "A LIFE engine could be designed to burn spent







This conceptual design shows a LIFE engine and power plant with a 1.4-megajoule laser system. At the facility's center is a fusion or fusion-fission target chamber. For efficiency sake, the balance of the plant (for turning heat into electrical power, as in all electrical power plants) would be sited as close as possible to the LIFE chamber, where the heat is produced. (Rendering by Kwei-Yu Chu.)

nuclear fuel and generate electricity while virtually eliminating all actinides,” says Latkowski.

LIFE engines would have enormous fuel flexibility. The fission blanket could consist of natural uranium, spent nuclear fuel (fuel no longer useful in a nuclear power plant and destined for a DOE waste repository), depleted uranium (mostly uranium-238, left over from the process used to enrich uranium for nuclear power plants), highly enriched uranium (rich in uranium-235), natural thorium, excess weapons plutonium, and other actinides. Using these materials, LIFE could supply U.S. electricity needs for more than 1,000 years.

### Extracting Nearly 100 Percent Energy

Depending on how it is configured a LIFE engine would require a ramp-up time of days to about 2 years before reaching full electrical power. If configured as a fusion-fission hybrid, the continuous power phase lasts for 5 to more than 40 years, followed by an incineration or burn-down phase in which nearly all actinides are converted to fission by-products. Because a LIFE engine can extract virtually 100 percent of the energy content of its fuel (compared to about 1 percent of a typical nuclear power plant), the nuclear waste it does produce has significantly reduced concentrations of long-lived actinides.

## How LIFE Works

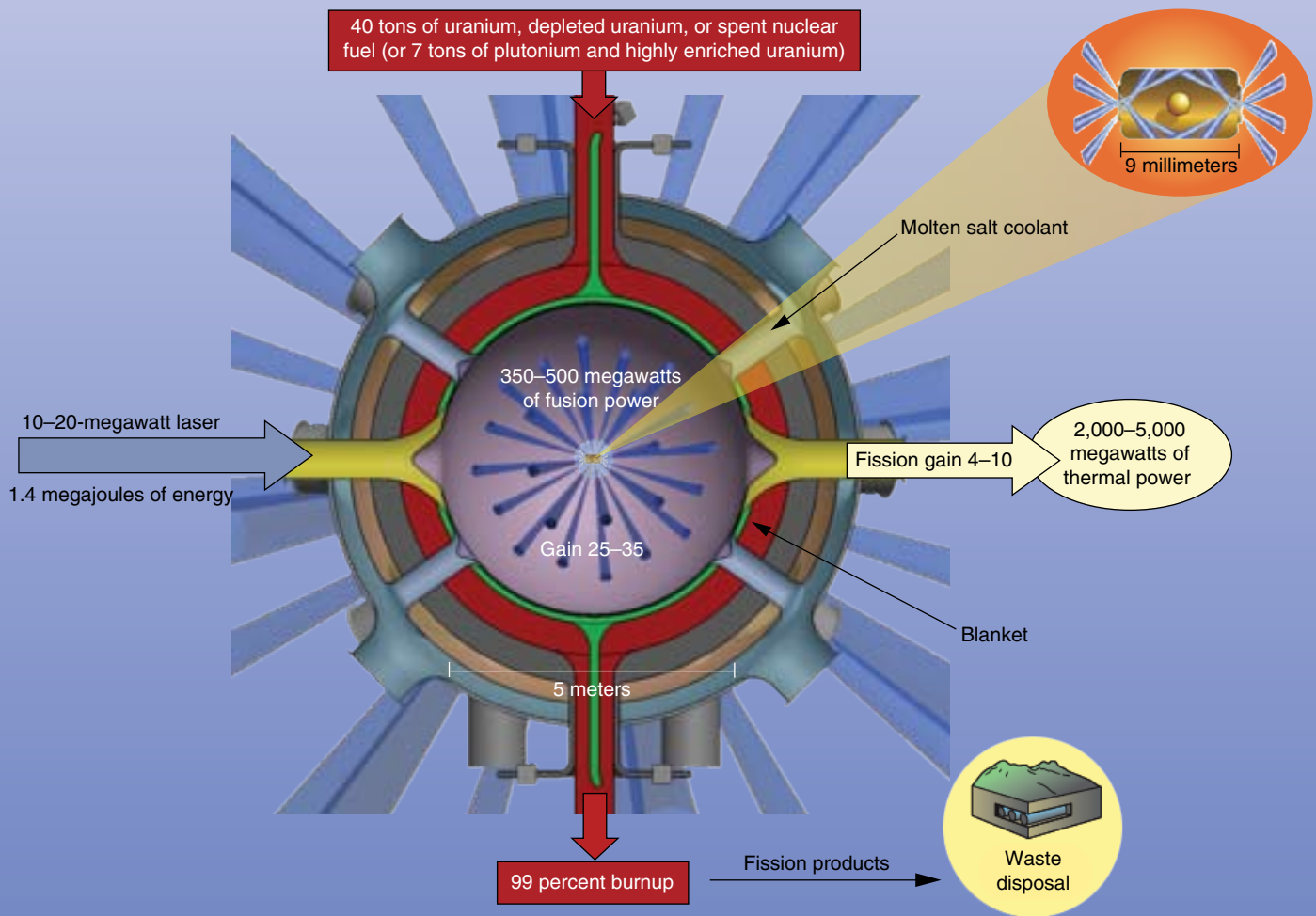
LIFE (Laser Inertial Fusion Energy) is an approach to pure fusion energy as well as a once-through, closed nuclear fuel cycle. A LIFE power plant comprises a solid-state laser system and a fusion target chamber that can be surrounded by a subcritical fission blanket. The balance of the plant includes a fusion target factory, a heat exchanger, and other systems.

The LIFE engine starts with a 10- to 20-megawatt diode-pumped solid-state laser system to provide about 1.4 megajoules of energy. Deuterium-tritium fusion targets are injected at 10 to 15 times a second into the center of a 2.5-meter-radius fusion chamber. The laser beams ignite the fusion targets to obtain energy gains of 25 to 35 and fusion yields of 35 to 50 megajoules of energy, thereby creating 350 to 500 megawatts of fusion power (about 80 percent in the form of fusion neutrons, with the rest of the energy in x rays and ions). Each fusion target generates about  $10^{19}$  neutrons.

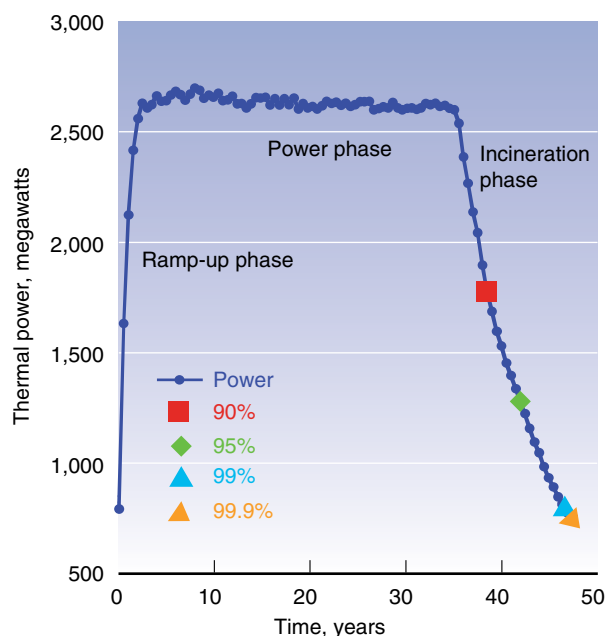
The fusion neutrons can also drive fission reactions in a surrounding subcritical fission blanket. The target chamber's

structural steel wall is made of low-activation oxide-dispersion-strengthened ferritic steel coated with 250 to 500 micrometers of tungsten to provide resistance to damage by high-energy fusion neutrons and the high temperatures resulting from absorption of the x rays emitted from the LIFE targets. The fusion neutrons pass through the first structural steel wall to a layer of metallic pebbles, which moderate the energy of the fusion neutrons and generate 1.8 neutrons for each neutron they absorb.

The moderated neutrons have a much lower energy spectrum than the fusion neutrons and are ideal for generating fission energy. These neutrons strike the 1-meter-thick subcritical fission blanket containing radiation-damage-resistant fission-fuel pebbles made from materials such as spent nuclear fuel and depleted uranium. The fuel pebbles absorb the neutrons to produce fissile material and drive fission reactions, which release heat to drive turbines. The pebbles are immersed in a molten salt that carries away heat and produces tritium. The tritium can then be harvested to manufacture new fusion targets.



The power curve for a typical LIFE power plant fueled by 40 metric tons of depleted uranium shows a ramp-up time of 1 to 2 years followed by decades of steady power and an incineration phase. Percentages show the fraction of initial fuel burned up.



Overall, a LIFE power plant would produce 20 times less nuclear waste per unit of electricity than existing light-water reactors, thereby drastically minimizing requirements for geologic waste repositories. The size of a repository needed to accommodate waste from an entire fleet of LIFE engines with the same generating capacity as the nation's light-water reactor fleet is about 5 percent of that required for disposal of spent nuclear fuel and would not be needed until the beginning of the 22nd century. Advanced ideas could reduce this need even further.

In addition, LIFE power plants would minimize nuclear proliferation concerns because of their closed, self-contained once-through fuel systems. LIFE engines do not require fuel enrichment before use, refueling during use, or fuel reprocessing after use. If solid fission fuel were used in LIFE power plants, it would be in the form of millions of fuel pebbles, each containing very small amounts of material. Each

pebble would be tagged as an accountable item, making it difficult to divert.

LIFE power plants also would avoid the criticality safety concerns associated with conventional nuclear reactors. LIFE's design requires firing the laser to generate neutrons that drive the fission reactions. The fission fuel is deeply subcritical; that is, it is incapable of spontaneously starting or sustaining a chain reaction. The fusion reaction lasts only for trillionths of a second and the fission reactions only for millionths of a second. When the laser stops firing, both fusion and fission reactions "instantly" cease. Residual heat is removed passively, so there is no possibility of a "meltdown" event.

### Team Taps Livermore's Strengths

Livermore's LIFE development team includes physicists, materials scientists, chemists, engineers, and energy and national security experts. Led by Moses and Tomás Díaz de la Rubia, chief

research and development officer for the Laboratory, the team has prepared a detailed cost and schedule road map, from system demonstrations of scaled pilot and prototype plants to final construction of the first commercial power plant. The first phase would include a combined physics performance, technology development, systems integration, and economic analysis program designed to assess the optimum configuration for commercial use of LIFE systems. Díaz de la Rubia notes that Livermore, teamed with sister DOE laboratories and academic and industrial partners, is uniquely qualified to meet such challenges with extensive experience in optics, photonics, and large laser projects; supercomputing and modeling; nuclear reactor physics; nuclear materials processing; high-energy-density physics; and materials science and engineering.

After fusion ignition and energy gain are demonstrated on NIF, several critical technological steps must be taken to achieve the first commercial LIFE engine by 2030. "Each of these steps seems likely to be achievable," says Díaz de la Rubia, "because the science and technology building blocks for a NIF-based LIFE system are logical and credible extensions of NIF technology as well as of ongoing developments in the worldwide laser and nuclear power industries."

Because the fusion and fission parts of LIFE are technologically and scientifically separable, progress can be achieved at the modular level in separate facilities. "The ability to separate LIFE subsystems makes a rapid demonstration path possible," says Moses. Demonstrating the required fusion performance can be achieved independently of each of the fusion technology systems, such as building a high-average-power laser or high-repetition-rate target capability.



To achieve a high shot rate, LIFE will use diode-pumped solid-state lasers (DPSSLs, invented at Livermore) cooled with flowing helium instead of the uncooled flashlamp-driven lasers used in NIF. Experts predict the cost of diodes will continue to decrease significantly, and many associated technologies have been demonstrated with the Laboratory's Mercury laser. In fact, over the past 12 months, the cost of laser diodes has come down by over an order of magnitude, driven by the increasing demand in the commercial sector for solid-state lasers and other applications of laser diodes. DPSSL technology, along with laser performance and reliability, can be demonstrated with a single beamline laser called a LIFElet. Scientists have begun exploring the requirements for designing a LIFElet laser.

A key technical challenge is developing the process for manufacturing and

injecting fusion targets into the center of the target chamber at 10 times per second, and then tracking them in flight for precise engagement by multiple laser beams. Livermore materials science experts, working with General Atomics in San Diego, California, have shown it feasible that fully automated, low-cost, large-volume target manufacturing can be adapted from the food and beverage and other mass-production industries. Researchers have begun using existing modeling codes for NIF fusion targets to design low-cost fusion targets for LIFE that would be scalable to mass production.

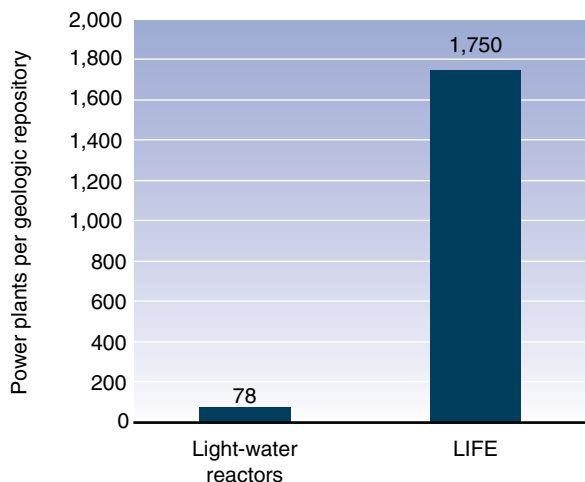
Target injection, steering, tracking, and engagement can be demonstrated with surrogate targets and low-power lasers in separate facilities. In this effort, Livermore partners are expected to play an important role. General Atomics has already demonstrated injecting targets at 6 times

per second. LIFE's target tracking system will likely take advantage of technologies, originally developed for other missions, to locate targets shot into the fusion-fission chamber with greater than 50-micrometer positional accuracy.

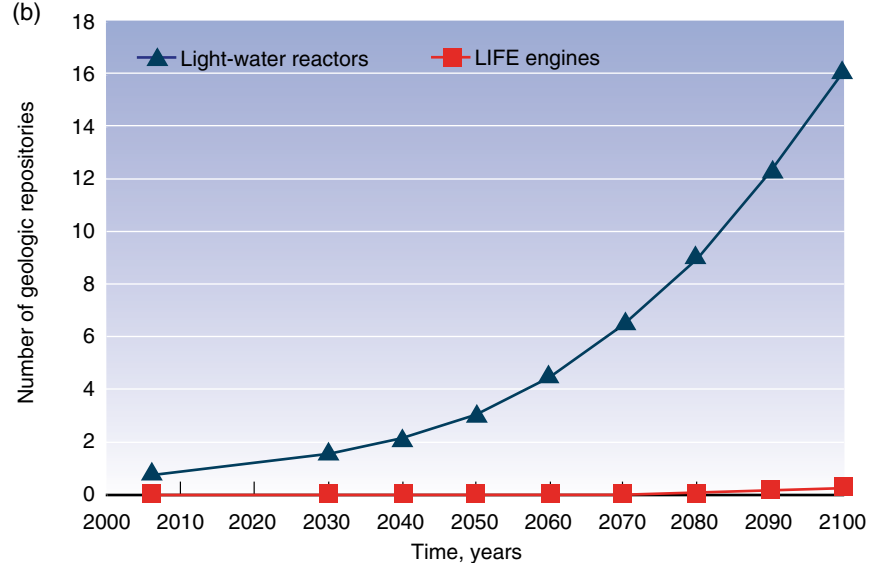
### Hot-Spot Ignition to Start

LIFE chief scientist Erik Storm, a preeminent member of the international inertial confinement fusion community, says the first experiments to demonstrate LIFE ignition and gain will use hot-spot ignition targets, the same as now planned for use in initial NIF experiments. In this design, a metallic shell about the size of a pencil eraser—called a hohlraum—surrounds a target capsule containing deuterium and tritium fuel. When irradiated by lasers, the hohlraum emits x rays that vaporize the outer layer of the peppercorn-size target capsule,

(a)



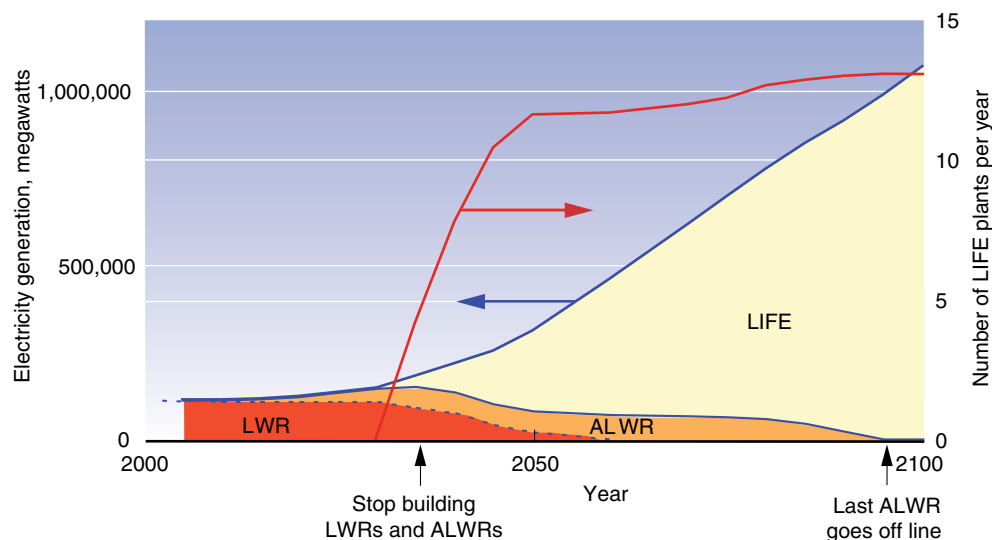
(b)



(a) LIFE extends the effective capacity of a deep geologic repository assumed to hold 70,000 metric tons of waste by as much as 20 times. (b) This graph shows the number of repositories required over the next century, assuming that the growing demand for electricity is supplied by a conventional fleet of light-water reactors or a fleet of LIFE engines.



Beginning in 2030, construction of 5 to 12 commercial LIFE plants annually could provide 1,000,000 megawatts of electricity (up to half of U.S. electricity demand) by 2100. Light-water reactors (LWRs) and proposed advanced light-water reactors (ALWRs) would be slowly phased out of commission. The red line signifies the number of LIFE plants to be constructed each year. The rate of construction steadily climbs until leveling off at a rate of about 13 new plants per year. During the construction peak of light-water reactor plants, about 10 to 15 were built per year.



causing it to rapidly implode. The resulting temperature and pressure forces the hydrogen nuclei to fuse and ignite in a controlled fusion reaction.

A different approach to ignition, called fast ignition, could reduce both the energy and the compression symmetry required to achieve ignition and would simplify the path toward pure fusion energy. In fast ignition, a standard laser pulse first compresses the target capsule's fuel. The fuel's plasma core is then ignited by an extremely short 10-picosecond high-intensity pulse from a second laser, much like an internal combustion engine. Plans are to demonstrate the physics basis of fast-ignition targets on NIF in conjunction with partners including the Laboratory for Laser Energetics at the University of Rochester. "Fast ignition may give us twice the gain for one-half the laser energy," says Storm. "It is not a requirement for a successful LIFE power plant, but if it works it will make pure fusion and compact fusion-fission systems even more economical and compelling."

Other development efforts will focus on issues associated with the operation of the fission blanket. Díaz de la Rubia says an important goal is to combine

theory, experiment, and simulation to develop new materials to achieve significant improvements in properties and performance.

The first wall of the fission blanket must be capable of withstanding high doses of fusion neutrons and temperatures up to 700°C. Accelerated testing with ion beams, coupled with multiscale modeling, will be used to design materials and simulate their property changes expected from the conditions within the target chamber.

Another challenge is designing, modeling, and testing high-temperature candidate fission fuels, which can be either in solid or liquid forms. Most analyses have focused on a solid fuel in the form of 2-centimeter-diameter fuel pebbles immersed in a liquid fluoride salt that carries away heat to drive electrical generators.

### The 2020 Vision

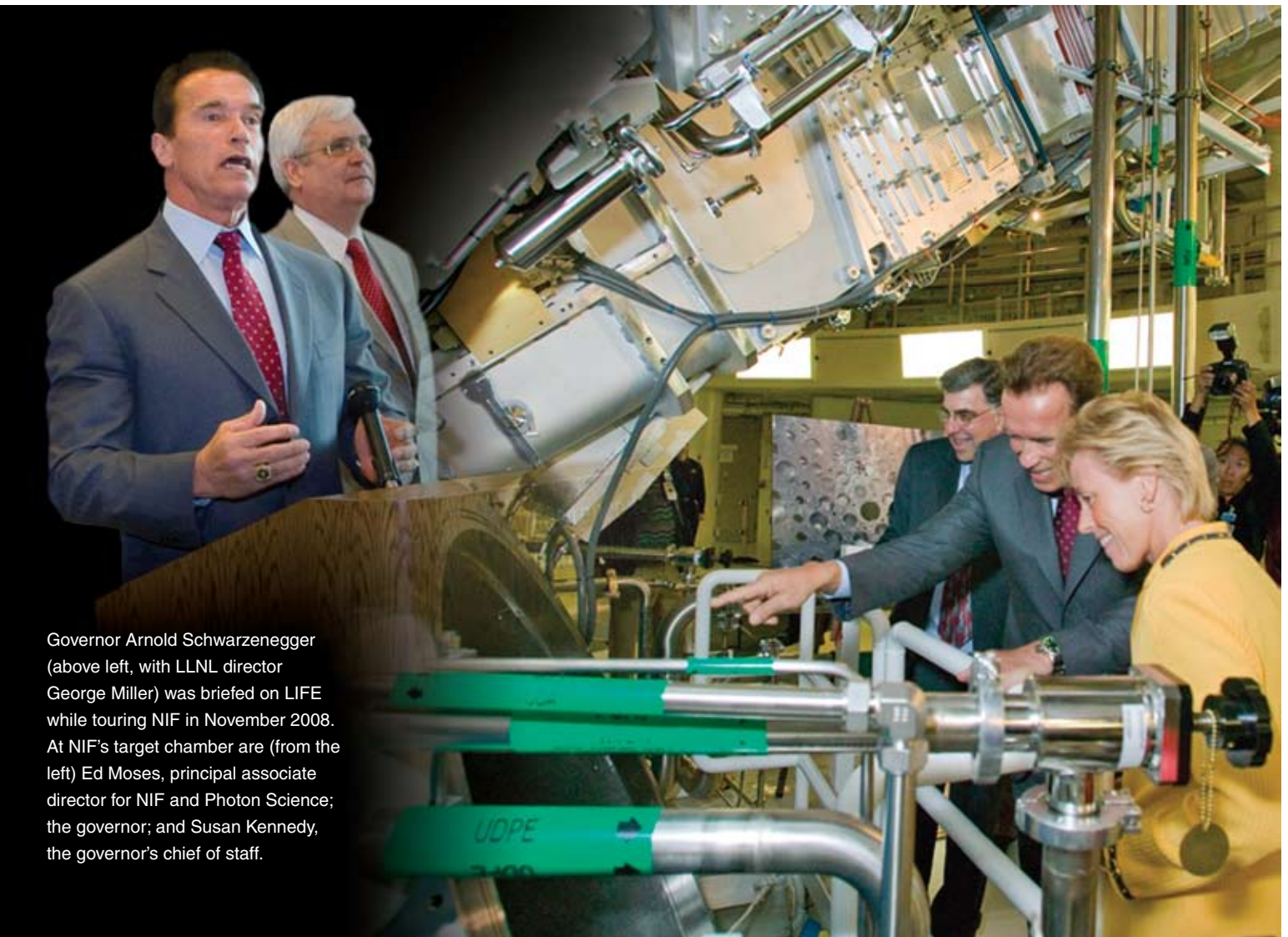
Demonstrating individual technologies would validate the subsystems required for LIFE, making possible an integrated prototype plant by 2020. This plant would be configured to test LIFE's energy-production systems operating 10 to

15 times a second. This plant could feature several aspects of various pure fusion and hybrid blankets operating at plant-performance specifications.

Beginning in 2030, annual construction of 5, rising eventually to 12, commercial plants could provide 1,000 gigawatts of electricity (about one-third to one-half of U.S. electricity demand) by 2100. A more ambitious option would supply about two-thirds of the nation's electricity demand by 2100. This option would require construction of 15 to 20 new LIFE plants per year beginning in 2030.

The Livermore team has held discussions with subject matter experts, utilities managers, energy experts, and senior members of the nonproliferation and diplomatic communities. Livermore scientists have addressed major technical symposia around the world.

A number of key officials have visited Livermore for briefings on LIFE. California Governor Arnold Schwarzenegger received a briefing when he toured NIF last November. The governor said LIFE could help meet the state's future energy needs while simultaneously decreasing dependence on fossil fuels. He added that fusion energy would contribute to reducing



Governor Arnold Schwarzenegger (above left, with LLNL director George Miller) was briefed on LIFE while touring NIF in November 2008. At NIF's target chamber are (from the left) Ed Moses, principal associate director for NIF and Photon Science; the governor; and Susan Kennedy, the governor's chief of staff.

greenhouse gas emissions. "This laser technology has the potential to revolutionize our energy future," said Schwarzenegger.

Thanks to advanced Livermore laser and fusion technologies and materials, an idea conceived more than 50 years ago now appears technically possible. By 2050, LIFE engines could be powering a substantial part of the U.S. and worldwide energy grid and supplying hydrogen fuel for transportation. At the same time, LIFE

engines could significantly reduce the amount of spent nuclear fuel awaiting long-term geologic storage. Livermore researchers are confident that LIFE may offer a pathway toward sustainable, safe, and carbon-free electric power.

—Arnie Heller

**Key Words:** diode-pumped solid-state lasers (DPSSLs), fast ignition, fission,

fusion, hohlraum, hot-spot ignition, inertial confinement fusion, Laser Inertial Fusion Energy (LIFE), National Ignition Facility (NIF), nuclear power, stockpile stewardship.

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